EXHIBIT 1

editorial

Reprinted from
Volume 31, Number 2, 1993

by J. D. Bredehoeft[a]
and L. F. Konikow[b]

GROUND-WATER MODELS: VALIDATE OR INVALIDATE

Validation

The word validation has a clear meaning to both the scientific community and the general public. Within the scientific community the validation of scientific theory has been the subject of philosophical debate. The philosopher of science, Karl Popper, argued that scientific theory cannot be validated, only invalidated. Popper's view is not the only opinion in this debate; however, many scientists today agree with Popper (including the authors).

To the general public, proclaiming that a ground-water model is *validated* carries with it an aura of correctness that we do not believe many of us who model would claim. We can place all the caveats we wish, but the public has its own understanding of what the word implies. Using the word *valid* with respect to models misleads the public; *verification* carries with it similar connotations as far as the public is concerned.

Our point is this: using the terms *validation* and *verification* are misleading, at best. These terms should be abandoned by the ground-water community.

History Matching

By stating that validation should be abandoned, we do not mean to imply that model testing and evaluation should be abandoned or that models are not useful. Far from it; both of us have spent much of our careers developing and using models for analysis. Models are adjusted until an *adequate* match to some set of historical data is achieved. To claim more for this process, using words like validate and verify, is to delude ourselves, mislead the public, and make us look foolish to our scientific colleagues. Petroleum engineers are much more modest, and term this process *history matching*. This, we feel, more aptly describes the modeling that hydrologists do.

Once an adequate match between historical data and model output is achieved, the model is commonly used to predict the response of the system into the future – often for some engineering purpose. Usually care is taken to predict only for a time comparable to the period that was matched. In other words, if we matched to a 10-year history, we would make a 10-year prediction with some confidence. In making longer predictions, one can expect that the cumulative errors arising from mistakes in the conceptual model, model structure, and parameter estimates

[a]Hydrodynamics Group, Sausalito, California; formerly, U.S. Geological Survey, Menlo Park, California.
[b]U.S. Geological Survey, Reston, Virginia.

GW editorials are the opinions of the authors, not the position of the AGWSE, NGWA, and/or the Ground Water Publishing Company.

could become significantly large. In the engineering community, the usual practice is to introduce a safety factor as insurance against our inability to predict accurately.

The ground-water community is attempting to place confidence bounds on predictions arising out of the uncertainty in parameter estimates. This is a welcome development; the single valued predictions of the past were overly simplistic. However, these confidence limits do not bound errors arising from the selection of a wrong conceptual model, or from problems arising with numerical solution algorithms.

Postaudits

Several postaudits have been performed to evaluate the accuracy of predictions made using supposedly "validated" models. Compared to the number of model studies, the number of postaudits is small. There are numerous problems in examining past predictions; often the stress placed on the system was quite different from that used in the model analysis.

The results of the current set of postaudits suggest that extrapolations into the future were rarely very accurate. There are various problems with the models: the period of history match was too short to capture an important element of the model, or the conceptual model was incomplete, or the parameters were not well-defined, etc. Our experience suggests that the models are more useful as tools used by the hydrologist to understand the system rather that as tools to predict future response. Our record of "validating" models is not encouraging.

Professional Judgment

The new computer methods, both for parameter estimation and for establishing confidence bounds for predictions, suggest to the uninitiated that the modeling process can be done with a minimum of human judgment. There are a number of important steps in modeling where professional judgments are critical. Among these are:

1. What constitutes the appropriate conceptual model? This is an *a priori* decision on the part of the modeler, a decision that at best can only be invalidated.
2. What constitutes an adequate match to the historical data? This is certainly a decision of judgment.

The point is – human subjectivity cannot be eliminated from the modeling process.

Society's actions will be based upon our professional judgments. Hopefully, our judgments will be grounded by insights gained from the best analytical tools available, including models.

Nuclear Wastes

Much of the current impetus for model validation has originated in the nuclear waste community. This discussion would be purely academic were it not for the fact that we, as ground-water hydrologists, are dealing with problems of great public importance with high public visibility.

The difficulty in the nuclear waste problem (as well as the toxic waste problem) is the fact that we are attempting to analyze the fate of wastes which are very long-lived in a geologic environment, an environment where there is uncertainty. We are asked to make to predictions for times of 10,000 years, or more. History matching followed by predictions of more or less equal duration is out of the question. It will be important to get the best possible conceptual model of the system. As suggested above, this is one of the most difficult of the modeling tasks.

In this arena, we must take special care not to mislead anyone by using words such as *validation* or *verification* that tends to imply to the uninitiated an aura of correctness that is nonexistent.

Editor's Note: This reprinted editorial from 1993 helps to celebrate the legacy of ideas that have influenced generations of hydrogeologists. Drs. Bredehoeft and Konikow kindly provided the following reflections on their editorial.

Reflections on Our Model Validation Editorial

By John D. Bredehoeft and Leonard F. Konikow

Since the Editorial was published in 1993, there has been a trend towards increased awareness of the fallacy of validation of groundwater models. But not everyone has heard or accepted the message. Publications since 1993 show that some authors, reviewers, and editors still present history matching as evidence of model validation. Furthermore, the development and application of improved statistical tools to simultaneously calibrate a model and estimate "best" values for hundreds, if not thousands, of parameters has facilitated the close match of simulated heads and flows to observed values. This can foster a false impression of how accurately and precisely one understands (and can predict future responses in) a complex heterogeneous groundwater system.

The critical decision in any modeling is the selection of the conceptual model, which is an a priori decision on the part of the analyst. One hopes that a bad conceptual model will be identified in the calibration process if the model projections do not fit the data, and the conceptual model is rejected. However, we recognize that even bad conceptual models can be calibrated and deemed acceptable. Another approach to the conceptualization problem entails establishing a set of conceptual models, and then using calibration to select the conceptual model, or models, that meet established criteria of acceptance. The problem is that one cannot be assured that the ensemble of conceptual models selected for consideration is all inclusive. And finally, when considering conceptual models, there is always the possibility of surprise – in which new data renders the prevailing conceptual model invalid. In the final analysis modeling involves inherent uncertainty that cannot be quantified; nevertheless, it is still useful and the best approach we have for synthesis, analysis, and testing our understanding. (April 29, 2012)